DISCUSSION

Geotechnical characterisation and engineering properties of Burswood clay

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‘Geotechnical characterisation and engineering properties of Burswood clay’ (Low *et al.*, 2011) is a valuable contribution as it contains a comprehensive set of geotechnical data on a 20 m thick silty clay deposit from Western Australia. Further interpretation of the laboratory and in situ measurements is justified.

SPECIMEN QUALITY ASSESSMENT

The authors defined specimen quality in terms of $\Delta e/e_0$ as opposed to the volumetric strain $\Delta e/(1+e_0)$, of a specimen subjected to the in situ effective stress condition in the oedometer, triaxial cell, or direct simple shear (DSS) device (Andresen & Kolstad, 1979), expressed in terms of specimen quality designation (SQD) A through E (Terzaghi *et al.*, 1996: p. 45). A detailed comparison of the advantages of $\Delta e/(1+e_0)$ or $\Delta e/e_0$, for assessing specimen quality is beyond the scope of this discussion. However, because the first discussor has previously assessed specimen quality using SQD for a large number of soft clay deposits (including specimens prepared from samples taken with the Sherbrooke and Laval samplers by technicians from the corresponding universities), it is of interest to assess using the SQD the quality of oedometer, triaxial and direct simple shear specimens of Burswood silty clay. Based on the data in Figs 3 and 4, out of some 36 specimens in Fig. 3 prepared from block samples, one qualifies as SQD A, 16 as SQD B and the remaining as SQD C. Note that samples are taken in the field; however, specimens following transportation, storage and preparation are tested in the laboratory. Considering that in the first discussor’s experience, the Sherbrooke sampler generally leads to SQD A specimens, disturbance was apparently associated with transportation, storage, or preparation of some of the Burswood silty clay specimens.

IN SITU COEFFICIENT OF EARTH PRESSURE AT REST K_0

The authors determined the in situ coefficient of earth pressure at rest $K_0 = \sigma'_{ho}/\sigma'_{vo}$ from self-boring pressure meter tests as well as laboratory tests (Fig. 9). However, in interpreting the K_0 data using the Schmidt (1966, 1967) equation, they state that ‘Based on the relationship suggested by Mayne & Kulhawy (1982) (i.e. $K_{0(OC)} = K_{0(NC)}(\text{OCR})^{\sin \phi'}$), the coefficient in equation (1) implies a friction angle of 23° or 24° which is much lower than measured in triaxial tests’ (30° to 53° from Fig. 19). This is not surprising because Mesri & Hayat (1993) demonstrated that the correct expression of the Jaky–Schmidt equation is

$$K_0 = (1 - \sin \phi'_{cv}) \text{OCR}^{\sin \phi'_{cv}} \quad (5)$$

where ϕ'_{cv} is the constant volume friction angle (e.g. to be determined using remoulded at liquid limit, normally consolidated clay specimens). Using the average plasticity index

$I_p = 52\%$ as suggested by the authors, $\phi'_{cv} = 25^\circ$ from the empirical correlation in Terzaghi *et al.* (1996: Fig. 19.7, p. 152) for Burswood silty clay

$$K_0 = 0.58 \text{OCR}^{0.42} \quad (6)$$

which is comparable to equation (1) of the original paper. Equation (6) predicts an in situ coefficient of earth pressure at rest in the range of 0.67 to 0.73 for σ'_p/σ'_{vo} in the range of 1.4 to 1.7 (or 0.65 to 0.71 for σ'_p/σ'_{vo} of 1.3 to 1.6 – see next section).

ONE-DIMENSIONAL CONSOLIDATION AND COMPRESSIBILITY

If, in fact, in the constant rate of strain (CRS) oedometer tests, the imposed vertical strain rate of $2.8 \times 10^{-6}/\text{s}$ resulted in a base excess porewater pressure ratio of less than 15% throughout the tests, then the imposed strain rate $\dot{\epsilon}_1$ was likely about ten times the strain rate $\dot{\epsilon}_p$ corresponding to the end-of-primary (EOP) consolidation (Mesri & Feng, 1986, 1992; Mesri *et al.*, 1994). Therefore, it may be necessary to multiply the values of preconsolidation pressure determined from the CRS tests by 0.90 to obtain the EOP σ'_p (Mesri & Choi, 1979, 1984; Mesri *et al.*, 1994).

Mesri *et al.* (1975: p. 541–542) introduced the comparison among the EOP e-log σ'_v curves of undisturbed, remoulded and sedimented specimens as a means of estimating the source of soil structure for a soft clay deposit. The comparison, of course, is expected to be done for specimens that are all prepared from the same sample, thus avoiding the need ‘To eliminate the effect of variation in soil type’ by introducing I_v . For characterisation of the mechanisms responsible for the soil structure and preconsolidation pressure of soft clay and silt deposits, Mesri *et al.* (1975) proposed a parameter termed liquidity index ratio (LIR) as the ratio of the liquidity index of the undisturbed specimen to the liquidity index of the sedimented specimen, both defined at the preconsolidation pressure σ'_p . For the undisturbed specimens of Mexico City clay, LIR averaged to 1.64, whereas for Leda clay from Gloucester, Ottawa, Canada, it was in the range of 2.22 to 2.47. For the moderately sensitive Mexico City clay, soil structure has developed as a result of sedimentation–primary consolidation (some chemical alteration), secondary compression and thixotropic hardening. The structure of the highly sensitive quick clays of Eastern Canada, including Leda clay, has developed through sedimentation–primary consolidation, secondary compression, interparticle bonding and leaching of the porewater. It would be instructive to know the LIR for the highly plastic Burswood silty clay (in the absence of data on a sedimented specimen, the e-log σ'_v curve of a specimen remoulded at natural water content may be used).

The best procedure for representing a non-linear relationship between void ratio and logarithm of effective vertical stress is either in terms of the e-log σ'_v curve or in terms of the secant compression index C'_c as a function of σ'_v/σ'_p (Mesri & Choi, 1985; Mesri *et al.*, 1994; Terzaghi *et al.*,

1996, pp. 107–108). The discussers cannot visualise a ready application for such information as the tangent compression index C_c at $3\sigma'_p$.

UNDRAINED SHEAR STRENGTH

The authors have plotted together the undrained shear strength data obtained by testing undisturbed specimens subjected before shear to the in situ effective stress condition, which are identified in terms of σ'_p/σ'_{v0} , and those obtained by the Shansep tests identified in terms of $\sigma'_{vm}/\sigma'_{vc}$ (or when tested in the recompression range of an undis-

turbed specimen, in terms of σ'_p/σ'_{vc}), where σ'_{vc} is a consolidation pressure. The former summarises undrained shear strength of a soft clay deposit as it may vary with depth, whereas the latter defines undrained shear strength in the recompression range as consolidation pressure σ'_{vc} increases from σ'_{v0} to σ'_p (Terzaghi *et al.*, 1996, pp. 166–173).

The discussers have replotted the undrained shear strength data from the laboratory triaxial compression (TC), direct simple shear (DSS) and triaxial extension (TE) tests on block samples, and from the field vane tests, in Figs 20(a)–20(d). In all cases, there is scatter in the data. Nevertheless, based on the assumption of $m_0 = 1.0$, values of 0.290,

Fig. 20. Undrained shear strength of Burswood silty clay obtained from: (a, b and c) laboratory tests on specimens prepared from block samples and subjected before shear to in situ effective stress condition, (a) triaxial compression tests; (b) direct simple shear tests; (c) triaxial extension tests; (d) field vane shear tests

0.276, 0.185 and 0.240, respectively, have been interpreted for $s_{u0}(TC)/\sigma'_p$, $s_{u0}(DSS)/\sigma'_p$, $s_{u0}(TE)/\sigma'_p$ and $s_{u0}(FV)/\sigma'_p$. In case it is accepted that the σ'_p from the CRS tests had been overestimated, then the undrained shear strength ratios are divided by 0.90 to obtain, respectively, 0.322, 0.307, 0.206 and 0.267. These values for the Burswood silty clay are comparable to those of other soft clay and silt deposits (Ladd, 1991; Terzaghi *et al.*, 1996: Figs 20.24 and 20.20); however, as compared to other clays with a plasticity index of 52%, $s_{u0}(DSS)/\sigma'_p$ of Burswood silty clay is too high and $s_{u0}(FV)/\sigma'_p$ is somewhat too low.

It is important to note that $m_0 = 1.0$ means s_{u0}/σ'_p of a soft clay deposit is independent of σ'_p/σ'_{v0} , whereas $m = 1.0$ means that for a soil element from certain depth s_u remains constant in the recompression range from σ'_{v0} to σ'_p , for example during precompression. Both undrained shear strength behaviours are generally true for soft clay and silt deposits with σ'_p/σ'_{v0} values typically less than about 3 (e.g., Terzaghi *et al.*, 1996: Figs 20.10 and 20.11).

Further, note that $m_0 = 1.0$ does not imply anything about the relationship between $s_{u0}(\text{test})$ and $s_{u0}(\text{mob})$, where $s_{u0}(\text{test})$ is measured by any laboratory or in situ test, and $s_{u0}(\text{mob})$ is mobilised in a full-scale field undrained failure. For example, according to Bjerrum (1972, 1973), a correction factor μ_B should be applied to $s_{u0}(FV)$ to obtain $s_{u0}(\text{mob})$ for stability analyses. The Bjerrum correction factor is 0.75 at $I_p = 52\%$. Therefore, based on the field vane tests the $s_{u0}(\text{mob})/\sigma'_p = 0.267 \times 0.75 = 0.200$ for Burswood silty clay. The same correction factor has been applied to the in situ vane shear data in Fig. 17, and is shown in Fig. 21.

The $s_{u0}(\text{mob})/\sigma'_p$ for stability analysis of an embankment on a soft clay deposit may also be estimated from the laboratory tests

$$s_{u0}(\text{mob})/\sigma'_p = \frac{1}{3} [s_{u0}(TC)/\sigma'_p + s_{u0}(DSS)/\sigma'_p + s_{u0}(TE)/\sigma'_p] \mu_t \quad (7)$$

where μ_t is a time to failure correction factor (Terzaghi *et al.*, 1996, p. 179). Based on the laboratory tests on block samples

Fig. 21. Mobilised undrained shear strength of Burswood silty clay determined from field vane and field cone penetration tests

$$\begin{aligned} s_{u0}(\text{mob})/\sigma'_p &= \frac{1}{3} (0.322 + 0.307 + 0.206) 0.87 \\ &= 0.242 \end{aligned}$$

In cases where data from DSS tests are not available, $s_{u0}(\text{mob})$ is computed from $s_{u0}(TC)$ and $s_{u0}(TE)$. In this case for Burswood silty clay $s_{u0}(\text{mob})/\sigma'_p = 0.230$.

In order to estimate s_{u0} from the in situ cone penetration test measurements, the authors divided the net cone resistance by 10. Mesri (2001) has derived for soft clay and silt deposits a cone factor of 16 ± 2 for estimating $s_{u0}(\text{mob})$ from the net cone tip resistance. Therefore, the s_{u0} data from the in situ cone penetration tests in Fig. 17 have been divided by 1.6 to obtain the $s_{u0}(\text{mob})$ shown in Fig. 21.

The $s_{u0}(\text{mob})/\sigma'_p = 0.200$ obtained by applying the Bjerrum correction factor to the field vane data is smaller than 0.22 that has been previously obtained (Mesri, 1975), and repeatedly confirmed, for a large number of soft clay and silt deposits. Furthermore, $s_{u0}(\text{mob})$ in Fig. 21 obtained by applying μ_B to $s_{u0}(FV)$ in Fig. 17, is smaller than the $s_{u0}(\text{mob})$ interpreted from the in situ cone penetration tests. The field vane tests in Burswood silty clay were performed using a rotation rate over 100 times the recommended standard, and then the measurements were corrected assuming 13% decrease in undrained shear strength for each order-of-magnitude decrease in strain rate. It is proposed here that the approximate nature of this strain rate correction procedure is responsible for the somewhat low values of $s_{u0}(FV)$ and $s_{u0}(FV)/\sigma'_p$ and the associated $s_{u0}(\text{mob})$ and $s_{u0}(\text{mob})/\sigma'_p$ for the Burswood silty clay.

Finally, it is of considerable interest to know the mineralogy of the Burswood silty clay with a reported activity range of 2.4 to 6.2.

Authors' reply

The authors thank the discussers for their interest in their paper and the excellent and constructive comments made. The authors value the additional analysis of the data they have conducted and have only minor responses to some of the points raised.

With regard to specimen quality, the authors' own experience is that certain clays, particularly sensitive Canadian clays that typically exhibit a degree of cementation, do indeed show SQD A using the Sherbrooke block sampler, but that for other soft clays the deduced sample quality often is less than SQD A. For example, in 2000 the authors collected Sherbrooke block samples of the cemented sensitive Leda clay from Gloucester, Canada, which is similar to many of the sensitive clays from Quebec, Canada that the first discussor has experience with. The Gloucester samples were transported 700 km by lorry to Massachusetts, USA, and all subsequently tested samples had SQD A quality. For the Burswood soil, which the authors believe is not cemented and has a fairly high silt content, similar transportation, storage and preparation methods were used as for the Gloucester samples. Of course, it is not readily possible to determine if the lower SQD B, and in some cases SQD C, ratings for the Burswood samples were partly attributable to disturbance during drilling and block sampling or disturbance during transportation, storage and preparation.

Although not mentioned in the paper, a K_0 consolidated triaxial test was carried out on reconstituted Burswood clay, consolidating it well into the normally consolidated region. The measured K_0 was about 0.55, while the critical state friction angle measured in the subsequent triaxial compression test gave $\phi'_{cv} = 32^\circ$. These values are not consistent with equation (5) and it appears that additional testing is

merited further to evaluate the K_0 - ϕ'_{cv} relationship for the Burswood clay.

Some adjustment of the preconsolidation stress, σ'_p , for strain rate effects might indeed be justified, although the authors suspect this would not be as much as the 0.93 factor empirically derived by Mesri & Feng (1992) or the lower 0.90 factor suggested by the discussers. While the target strain rate in the CRS tests was indeed close to the $10\dot{\epsilon}_p$ rate of $2.5 \times 10^{-6}/s$ suggested by Mesri & Feng (1986) for soft clays, the excess pore pressure ratios close to σ'_p for a majority of the tests on the Burswood samples were actually less than 3% (for tests on block samples, five tests with ratios < 3%; three tests between 3 and 12%). The authors are not able to quote a reliable LIR value for Burswood clay, as only one test on a remoulded sample was undertaken. The authors agree that the tangent compression index, C_c , at a stress of $3\sigma'_p$ was somewhat arbitrary, but space did not permit an additional plot of C_c as a function of normalised vertical effective stress.

The authors do not have any specific responses in respect of the discussers' comments on the undrained shear strength ratios reported for Burswood clay in the paper. There are indeed many considerations such as adjustments for strain rate effects and whether an assumed or 'best fit' m value is adopted. Note that although the authors quoted 'best fit' m values exceeding unity in Table 5, these are not considered to be plausible and indeed they correspond to the lowest R^2 values. In addition, the authors would also like to point out that the nominal N_{kt} of 10 was simply adopted for data presentation purposes. The Burswood site-specific N_{kt} values are presented in Table 6.

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